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ELECTROMETER TUBES: PART I

by

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1. Introduction

The term "electrometer tubes" (ER) here designates electronic tubes where the operational control-grid current is smaller than 10^{-14}A and where the control grid in the cold state has an insulation resistance of more than 10^{14} ohm to all other electrodes and the ground. Tubes with higher grid currents (Frommhold /4/ has proposed the term "galvanometer tubes" for those with grid currents between 10^{-10} and 10^{-14}A) are not treated herein.

Allegedly, Hausser, Jaeger and Vahle /6/ first reported on efforts to design tubes with a very small grid current. Very soon models of German, American, Japanese, Hungarian, Dutch and other manufacturers came on the market. Many communications reported on attempts to perfect electrometer tubes. In part due to the outbreak of war in 1939 and in part also because of the relatively small number of purchasers of such tubes, industry did mot utilize these investigations very much and the greater part of them were forgotten. With the progressive development of modern measuring methods, especially in the field of nuclear research and radiation measurement but also in some technical fields, greater interest in electrometer tubes was to be expected and became manifest towards the end of the 1950's. However, now there is a difficulty of a new type

which interferes with further improvement. The production of electrometer tubes of an individual manufacturer is still too small to justify the development of special automatic machines. Present-day electrometer tubes are primarily produced on standard automatic machines and special designs are possible only with considerable difficulties. This somewhat reduces the hope of definitely overcoming the "infantile diseases" of these tubes unless countries with lower wage scales enter the field. Once these infantile diseases are overcome, we must hope that interest in the electrometer tube will increase to the point where full-automatic production becomes profitable. This would be an advantage because electrometer tubes are superior to all others for certain purposes.

The main field of utilization of the electrometer tubes is constituted by the measurement and continuous recording of extremely small currents (and correspondingly small charges) and of medium voltages originating from sources with high internal resistance, i.e., in electrometric circuits of all kinds.

Some preferred utilizations are found in geophysics and astrophysics (atmospheric electricity, earth currents, certain electric subsoil-investigation methods, satellite techniques, optic-astronomic measurement in gas-discharge physics and in radiometrics (ionization chambers, investigations of the non-autonomous and of the Townsend domain of autonomous gas discharges, corona discharges), of nuclear physics (mass spectroscopy) and in all other fields of physics in which they frequently replace the well known electrometers. The electrometer tubes can serve equally well in electrochemical (glass electrodes) and electrobiological (plant and animal physiology) investigations. In technology, electrometer tubes are found in instruments for radiation measurement, piezoelectric pressure meters, tera-ohm meters, etc.

2. Comparison with Electrometers

"Electromechanical" electrometers based on electrostatic attraction (coulomb forces) have a considerable advantage by comparison with the electrometer tubes. They are easier to examine and failures are easier to find. However, this is not true for all metrological problems and should not cause us to overlook the unfavorable properties of the electrometers. Electrometers also have a zero-point drift which is due not only to temperature effects, temperature exchange processes, mechanical fatigue of elastic components, the flow /creep?/ of insulating substances and adhesives as well as changes in secondary voltages but also to the variable Volta potentials and the charges linked to them, to variable Volta currents (because the air space between the electrodes is ionized) piezopotentials, thermic currents, the finite conductivity of air and to other factors. These effects are often more important than expected. We also tend to overlook that the motion of a charged electrode represents a current. During rapid variations, the displacement currents can therefore assume appreciable values. If we take all this into account, we can then--at least for the fields in which these effects are active--still consider the electrometer tubes as a "simpler" instrument. The grid current I_G can be determined--although of complex composition of different constituents--by only a few characteristics and can be established, e.g., for the electrometer tetrode through $I_G = f(I_F, U_R, U_G, U_A)$, as soon as certain extraneous conditions have been fulfilled. (Since a space-charge grid frequently occurs as G-1 in the electrometer tube, we prefer the letters R,G,S,B, for the identification of the grids to the numbering as G-1, G-2, G-3.) The electrometer tubes further have the well known advantages of being independent of position,

of greater resistance to impact, of being small, of having low weight, of being relatively inexpensive and of permitting, with simpler means, the control of such instruments as recorders, amplifiers, data transmitters, etc. (It is, of course, perfectly understood that a good electrometer should be available in any laboratory which works with electrometric circuits.)

3. Range of Measurement

a) Voltages from sources in which the internal resistance is small against the quotient $\frac{-U_G}{I_G}$ of the electrometer tubes, can be measured or recorded with the electrometer tubes if they are connected between control grid (G) and cathode (generally directly heated) (F), usually in series with the grid-bias battery. If the resistance of the source permits this, we connect G and F by a maximum-ohm resistance and so determine the grid potential when the measured value is lacking. (From grid-bias and voltage drop of the grid currents in the maximum-ohm resistance).

The upper limit for such voltage measurements lies at about 2 Volt. However, with a maximum-ohm potientiometer, we can measure any high voltages but the result will include the inaccuracy and the absence of constancy of such maximum-ohm resistances. For "inverted triodes" (cf. 6-a), the maximum voltage, capable of being measured directly, lies higher by about two powers of ten. It is difficult to say where the lower limit is. Much effort has been expended to place it very low (values of 10^{-6} Volt are cited in literature), by utilizing, among other means, very sensitive mirror galvanometers for the measurement of the plate current (with compensated spacing current).

There remains the question whether this still serves any purpose in an electrometric circuit. When it becomes necessary to measure voltage sources of extremely high resistance, such high disturbing voltages become admixed to the impulse voltage merely through the material-electric effects in the generator and in the circuit that we run the risk of blanking out the impulse voltage. This is not alone a property of the electrometers but is equally true for all electrometric voltage measurements. We are inclined consequently to set 1 mV as lower limit but recommend not to go below the range of 10 or even 50 mV, unless it is absolutely necessary.

b) Currents should be measured either by a charging method (i.e., according to 3-c) or as voltage drop in a maximum-ohm resistance. We can therefore measure only the currents of electric circuits which are compatible with these high resistances. If we desire an accuracy of measurement within 1%, then the smallest measurable currents are 100 times the (unknown) variations of the grid current. If we assume for these variations 10% of the grid current, we will then still be able to measure currents of about 10^{-14}A if the grid current of the electrometer tube has 10^{-15}A.

If we obtain (which is possible in the laboratory with the necessary care) almost constant grid currents of 10^{-17}A, we should then be still able to measure a current of 100 elementary charges per second. If the electrometer tube is controlled with 1 V, we then require a maximum-ohm resistance of 10^{14} ohm for measuring a current of 10^{-14}A and the inaccuracy and inconsistency of the resistance will influence the measured result. During more prolonged recording, we may therefore anticipate--not only with electrometer tubes but also with other electrometric measuring

methods--an accurate determination of currents down to 10^{-14}A.

c) Charges: The capacity of the control grid of the electrometer tubes is small compared to other electrodes and a minor increase of charge already results in a measurable displacement of the grid potential (10^{-12}C corresponds to about 100 mV). This charge is varied through the grid current so that the limit for the measurement of the charge or of the current in the charging method is determined by the necessary measurement interval. If the measurement can be effected in 1/10 sec., we should then still be able to measure, under laboratory conditions, (theoretically) 10 elementary charges but, in practice and for the reasons stated above, it will be difficult to go below 10^{-15}C.

4. Grid Current

a) Composition of grid current: In our opinion, the best study on the composition of the grid current of an electrometer tube is that of Frommhold /4/ which is unfortunately not easily accessible. According to him, the grid current is composed of the following constituents:

1. Insulation currents
   - 11. To the cathode;
   - 12. To the anode, space-charge grid, screen grid.
2. Currents which make the grid potential more negative (also called "positive grid currents;" in our opinion, an unfortunate term for the transport of negative charges from plus to minus);
   - 21. Starting current.
3. Currents which make the grid potential more positive (also called "negative grid currents");
   - 31. Cathodic flux through:
     - 311. Electron impact on the molecules of the residual gas;

312. Positive ions emitted by the cathode;

313. Thermic ions through impingement of gas molecules on the hot cathode;

314. Creation of ions through radioactive and through cosmic radiation.

32. Current through thermic grid emission due to temperature radiation from the cathode.

33. Photoelectron emission from the grid through:

331. The light of the cathode;

332. Radiation from extraneous sources;

333. Light quanta from excited molecules of the residual gas;

334. Quanta of the ultra-soft Bremsstrahlung /moderation/ of the electrons impinging on the anode or the space-charge or screen grids.

The magnitude of the constituents greatly depends on the grid potential and also on the geometry and material of the tubes and electrodes. It is therefore almost impossible to furnish general data. Indications and formulae will be found in Frommhold /4/ who also gives suggestions for the reduction of the constituents (cf. 6-b). Fig. 1 shows a schematic representation of the constituents.

b) Measurement of grid current: If we vary the maximum ohm resistance, through which the grid current is reconducted to the cathode, and simultaneously keep the grid potential constant through adjustment of the grid bias (in such manner that the anode current remains the same), then the required variation of the grid bias affords a measure for the voltage drop created by the grid current in the maximum-ohm resistance. The value of

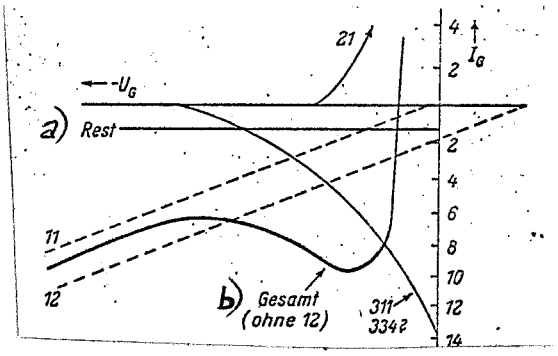

Fig. 1. Schematic representation of grid-current constituents according to Frommhold/4/.

11 = insulation currents to cathode; 12 = insulation currents to anode, to the space-charge and to the screen grids; 21 = starting current; 311 = cathodic flux through electron impact; 334 = photoelectron emission of grid through quanta of ultra-soft Bremsstrahlung.

a = residue; b = total (without 12).

the maximum-ohm resistance, inclusive of its dependence on voltage and temperature, must be known sufficiently accurately.

There are further prerequisites for this method. The electrometer tube must have been installed under operational conditions (cf. 5-a). Zero-point shifts due to changes of input voltage and other reasons must be smaller than the measurement effect to be calculated which will be indicated by a test measurement with short-circuited grid. The grid/cathode capacity should be enlarged during measurement by a condenser, in order to reduce the influence of residual charges, but such a condenser must be free of remanence, have no disturbing volta potential, etc., and its value may amount to about 20 pF. The electrometer tube must have been adequately warmed up before measuring (cf. 5-a).

A method indicated by Holik /7/ and discussed by Schintlmeister /13/ does not require a maximum-ohm resistance. In it, a capacitance connected between grid and cathode is held at a constant tension through generation of influence charges. Volta potentials and polarization phenomena in the dielectric cause interference here.

c) Note on indication of grid current. Customarily, the designation "grid current" groups all the constituents listed in 4-a and there are good reasons for this. However, for the comprehension of some electrometer-tube circuits, it would be advantageous, and simpler for practical calculation, if we would include only groups 2 and 3 and leave out the insulation current (group 1). Obviously, an electrometer tube would then have to be characterized, in addition to the indication of the grid current so defined, by data on the insulation resistance between grid and cathode and between grid and positive electrodes. In operation, this insulation resistance becomes parallel to some other resistances (and only this parallel circuit is effective) such as generator resistance, insulation resistance of wiring, switches, connectors, condensers, supports, etc., inclusive of conductance by air and, in general, specially built-in defined grid-leakage resistance. The fundamental impossibility of considering the insulation resistance in the tube (whose value is embodied in the customary indication of grid current) without its shunts, easily leads to erroneous conceptions, particularly in regard to operation of the electrometer tube with "floating" grid (cf. 5-e).

d) Variation phenomena. The resistance noise in an exterior grid-leakage resistance does not directly belong to the electrometer tube. However, there are tube-inherent variation phenomena, represented customarily by generators in the substitute circuit diagram, acting on the control grid, although their physical effectiveness may be an entirely different one. Kronenberger /9/ lists the following: shot effect of the tube, distribution noise of the grid current, flicker effect of the tube, abnormal flicker effect of the tube, effect of emission-drift of the tube. The effects of flicker and of emission-drift can be neglected in

electrometer tubes which do not have oxide cathodes. For details, cf. Schintlmeister /13/ (p. 120 ff.).

5. Circuitry and Operation

When utilizing electrometer tubes in circuits, special precautions must be taken which are not necessarily very difficult but are not customary in working with other tubes.

a) Warm-up. A new or cold (out of operation for more than several days) electrometer tube must be first warmed up, in general for several hours. The necessity for this arises probably from the fact that residual gas molecules are expelled from the electrodes only after the cathode is hot.

Warm-up must continue until zero drift has stopped and should take place under standard conditions of subsequent operation. An effort should be made to utilize electrometer tubes in continuous operation. In our experience, performance data of electrometer tubes become more constant and the grid currents lower when an electrometer tube stays in continuous operation for several months (it also appears that tube life is much longer than indicated by the manufacturers).

b) Maintaining proper insulation of bulb. The insulation of the bulb and control grid is affected by atmospheric moisture and by traces of organic substances and vapors. Air moisture around the electrometer tube should not be more than 20% at standard atmospheric pressure (drying by chemicals or through heating which is inherent in many instruments). Organic substances are easily transmitted from the hands to the bulb and form a thin film on the latter. Electrometer tubes should be handled preferably in a protective covering, removed after installation, or by wearing washable gloves. Traces of soldering flux, e.g., colophony, may

reach critical points along connecting wires as well as through condensation of vapors. Protective paper sleeves or covering of the wires (remove both after installation!) and very careful cleaning of the soldered contact are helpful but it is safer to use clamp connections instead of soldering.

If the bulb has become contaminated, it should first be checked to see whether it has a protective film (silicon, ceresin or other water-repellent substances) which should not be damaged, if possible. If necessary, when the bulb is very dirty, spots are removed with a suitable solvent. The bulb must then be immersed in 96% alcohol (vessel must be large enough so that dirt from previous cleanings can sediment) and subsequently washed with double-distilled water. Drying with warm air completely free from dust is recommended and is sufficient in many cases.

c) Shielding. Increase of grid current through extraneous radiation should be prevented as far as possible through shielding. A very fine light ray penetrating through a small gap may cause variations of more than 50%. The same is true of all types of radioactive radiation (particle radiation, gamma rays, x-rays, etc.). The electrometer tube should also be shielded against electric or magnetic fields.

d) Activation of supply voltage. During the time required for the cathode of an electrometer tube to become fully heated, no tension should exist between the cathode and other electrodes. Otherwise the initially emitting islands may burn out with consequent alteration of tube characteristics. To start operation, we first activate the heating voltage, after several seconds the grid bias and then the positive voltages and deactivate in reverse order. A very large condenser parallel to the filament (1 mF or higher) more or less guarantees this sequence in case of sudden failure of the supply voltage but prolongs the warm-up interval.

e) Tube fuses. Electrometer tubes are expensive and their filaments burn out relatively easily. They can be protected against voltage surges by means of the so-called "ultrafine" fuses available commercially. However, the risk remains that the damage referred to in the previous paragraph may occur. It should be remembered that these "ultrafine" fuses have a relatively high resistance (12-mA fuse = 35 ohm).

f) General switching instructions. In the design and construction of circuits containing electrometer tubes, the special conditions valid for all electrometric circuits must be kept in mind. /3/.

Because tube manufacturers concentrate on proper insulation of the control grid to ground, a grounded grid circuit would be impractical for electrometer tubes but grounded cathode or anode circuits are possible in the same way.

No voltages should occur in the electrometer tube which are higher than the excitation voltage of the residual gas because the grid current is increased otherwise. The anode voltage should be set at a maximum of not more than 5.5 V and the other positive voltages at the same rate or lower. Even then the yield of Bremsstrahlung is undesirably high but, with the electrometer tubes commercially available today, it is scarcely possible to come down with the anode voltage so far that this is also appreciably lowered--amplification then becomes insufficient. For electrometer tubes coupled with a working resistance, the battery voltage must be determined from these requirements by taking into account the plate current to be expected.

The low anode voltage leads to the fact that its effect on the emission of the cathode is different at the two ends and along the length of the latter (all voltages are always referred to the negative filament

end). More cathode current comes from the negative than from the positive half of the filament and the former therefore becomes hotter. This difficulty may possibly be a large part of the reason for the regrettable individual differences of two units of the same type of electrometer tube which necessitates recalibration when changing tubes.

In order to exercise the necessary care during calibration, an extreme high resistance should be connected between the calibration-voltage source and the grid so as to prevent the grid-leakage resistance R_G (cf. /8/, Fig. 1, for determination of voltage drop occurring here) from being shunted through the internal resistance of the calibration-voltage source. Because of the considerable difficulties this causes in calibration, this is generally omitted and instead we calculate the intensity of the grid current during calibration mathematically by establishing, for example, the calibration voltage as additional grid bias so that R_G itself lies between the calibration-voltage source and the control grid.

If the capacity of the control grid of the electrometer tube is a primary consideration in a circuit (in particular for measurement of charge), we should remember that the "dynamic" capacity during operation is generally appreciably greater than the "static" capacity measured on the cold tube. Schintlmeister /13/ discusses this in detail on the basis (p. 116) of the various pertinent reasons (space-charge clouds, anode reaction).

Amplification through electrometer tubes concerns as a rule pure output amplification (current amplification, resistance transformation) with a voltage-amplification degree of $\mu \approx 1$, occasionally even $\mu < 1$. Only circuits with electrometer pentodes are an exception to this.